



Experimental Methods in Reduced-Gravity Soldering Research

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ABSTRACT

The National Center for Microgravity Research, NASA's Glenn Research Center, and NASA's Johnson Space Center are conducting an experimental program to explore the influence of reduced gravity environments on the soldering process. An improved understanding of the effects of the acceleration environment is important to application of soldering during current and future human space missions. Solder joint characteristics that are being considered include solder fillet geometry, porosity, and microstructural features. Both through-hole and surface mounted devices are being investigated.

This paper focuses on the experimental methodology employed in this project and the results of macroscopic sample examination. The specific soldering process, sample configurations, materials, and equipment were selected to be consistent with those currently on-orbit. Other apparatus was incorporated to meet requirements imposed by operation onboard NASA's KC-135 research aircraft and instrumentation was provided to monitor both the atmospheric and acceleration environments. The contingent of test operators was selected to include both highly skilled technicians and less skilled individuals to provide a population cross-section that would be representative of the skill mix that might be encountered in space mission crews.

INTRODUCTION

Future long-duration human exploration missions will be challenged by constraints on mass and volume allocations available for spare parts. Addressing this challenge will be critical to the success of these missions. As a result, it is necessary to consider new approaches to spacecraft maintenance and repair that reduce the need for large replacement components. On the International Space Station the maintenance concept for avionics has evolved from removal and replacement of entire Orbital Replacement Units (ORU's) to removal and replacement of circuit cards when possible. The next step to reducing the size of the items being replaced would be to implement component-level repair, which is the repair mode used by the U.S. Navy on vessels at sea. Factors in the decision to implement component level repair include operational issues (such as skill requirements and crew training), systems issues (including fault diagnosis and post-repair verification), and process issues (including potential influences of a reduced gravity environment on the metallurgical characteristics and configuration of solder joints). The process issues are the thrust of this project.

BACKGROUND

Several automated on-orbit soldering experiments have been conducted since the beginning of the Shuttle program with experiments flying on STS-4, -7, -11, -17, and -40 (Ref. 1). Some of these experiments malfunctioned and yielded no results. Others functioned nominally but post-flight analyses were not performed, were not reported, or only considered gross macroscopic effects. The dominance of surface tension was noted (allowing filling of wider gaps than would be possible in normal gravity), as well as an increased entrapment of flux in the solidified joints. These experiments were conducted in vacuum; their applicability to practical repair operations is therefore limited since such operations would be carried out in a pressurized “shirtsleeve” environment.

A manual soldering experiment was conducted on STS-57. In this effort, a crewmember soldered and de-soldered a variety of samples mounted on circuit cards. These tests were started in an onboard glove box, but the crewmember concluded the tests in the open cabin environment. The samples included various electronic devices and wire junctions. A review of videotapes made during the course of the experiment yields some interesting qualitative observations based on the crewmember’s comments. First, the molten solder alloy appeared to solidify at a slower rate than during 1-g training. Second, the solder fillets appeared to be more “convex” than in 1-g.

This paper will compare the external joint geometry, cooling rates, and flux entrapment characteristics of solder joints produced in reduced gravity to those produced in normal gravity.

TECHNICAL APPROACH

Aircraft Facilities

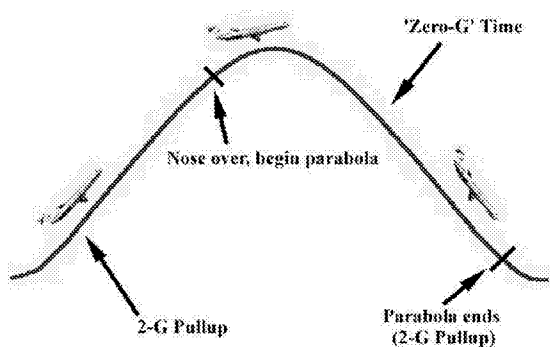


Figure 1
Schematic of aircraft trajectory during
reduced-gravity maneuvers

Flying an aircraft (NASA’s KC-135) in a parabolic trajectory generates the reduced gravity environment (Ref. 2, 3). The maneuver starts with a full power climb, after which the nose is lowered to trace the parabolic arc (Figure 1). From the time that the nose begins to lower, until the pullout (from the ensuing ‘dive’ on the back side of the trajectory), the experiment and crew experience a 20-25 second period of ‘reduced gravity’, relative to their surroundings. While the acceleration levels experienced during these maneuvers are qualitatively very low, some residual accelerations (engine and airframe vibrations, etc) remain.

Experimental Hardware

The experimental apparatus (Figure 2) provides accommodations for a test operator, who is seated and strapped to a seat, to manually solder on a circuit board in an enclosed glove box. The test operator places their hands into the glove box via two access holes. The soldering iron is a Weller® TCP 12P with a PTP7 tip and is the same model as currently flown in the soldering kit aboard the International Space Station. The glove box is vented between tests via an overboard vent valve. The apparatus includes video recording of each solder joint, glove box temperature, relative humidity, and ambient pressure. On select joints, thermocouples were spot welded or soldered to the circuit board pad to obtain heating and cooling profiles of the solder

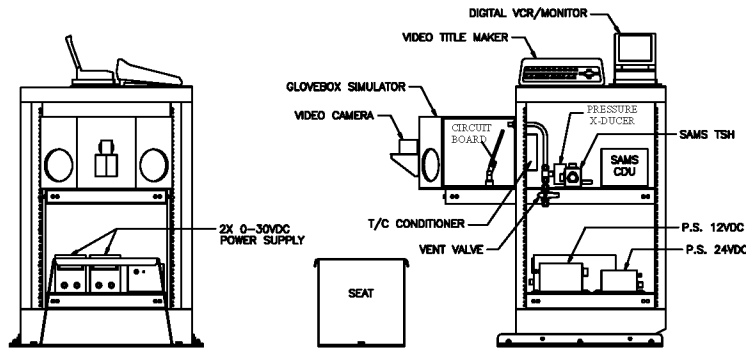


Figure 2
Experimental Hardware used on KC-135 Aircraft

circuit board. The components consisted of resistors that were fastened to the sample card using an epoxy. Future tests will examine surface mount device (SMD) configurations.

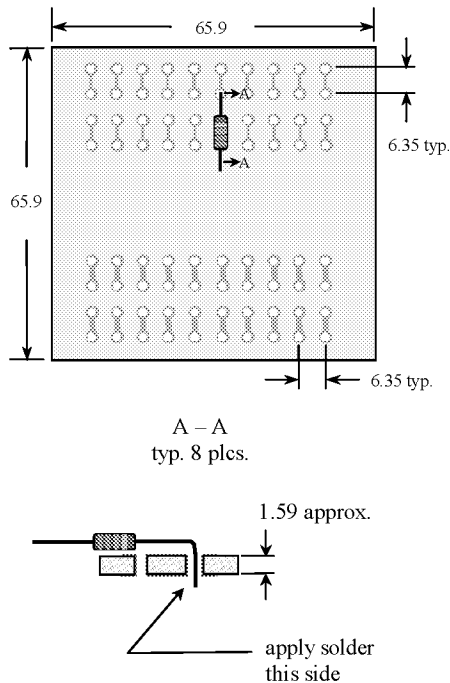


Figure 3
Plated through-hole sample configuration
(all dimensions in millimeters).

joint. Additionally, the Space Acceleration Measurement System (SAMS) program at NASA GRC provided a 3-axis accelerometer for local acceleration measurements.

A “plated through-hole” configuration (Figure 3) has been used as the standard test configuration. This arrangement is representative of a typical service joint on an electrical

The primary solder alloy consisted of Sn/Pb 60/40 with a resin flux core. Select samples used a eutectic composition of Sn/Pb 63/37 solder again with a resin flux core. Additional tests were conducted using a solid core solder (Sn/Pb 60/40). During these tests, liquid flux was applied to the solder joint prior to heating and adding solder to the joint. Application of the solder flux was primarily done during the 2-g pull-up just prior to the reduced gravity portion of a parabola on the KC-135 aircraft. During select tests, the liquid flux was applied in reduced gravity to observe the flowing characteristics of the flux. Results of the solid-core soldering are currently being investigated and are not reported.

In addition to low-gravity testing, samples were also soldered under normal gravity conditions while onboard the KC-135 aircraft to determine a baseline sample set for comparison. Initially, normal gravity tests were conducted in the same orientation as during reduced gravity tests with the circuit board at approximately a 53° angle relative to the horizontal (as shown in Figure 2). During all subsequent testing, the sample card was positioned in the horizontal plane for the normal gravity tests, allowing the gravity vector to be perpendicular to the circuit board.

Multiple operators were used during the testing. The effect of operator skill was characterized by using multiple ‘unskilled’ operators (all of whom attended a common training class, similar to the training given to astronauts), as well as a “skilled” technician, who is qualified to solder space flight hardware. Since this effort is designed to evaluate the practical aspects of soldering

by an astronaut, control of operational parameters (dwell time of soldering iron on joint, amount of solder added, etc) were at the test operator's discretion. The mass of solder added, while not controlled, was determined by measurement (before and after the test) of the mass of the solder piece used.

Post-flight analysis (done jointly at NASA Glenn and NASA Johnson) consists of a visual inspection, photography, and leg-length measurements of the soldered joints, followed by cross-sectioning / porosity measurements and optical metallographic characterization. Metallographic analysis will be presented in a future paper.

RESULTS

Testing was performed with the plated through hole configuration using five test operators. A total of 297 reduced gravity samples and 143 normal gravity samples were obtained using the resin-flux cored solder. In these tests, a higher incidence of porosity occurred in reduced gravity compared with normal gravity (see below). In an attempt to mitigate the increase in porosity, tests were conducted using a solid core wire with flux applied externally to the joint producing 160 reduced gravity samples and 64 normal gravity samples. The results of the solid core wire soldering are currently under analysis.

Acceleration Environment

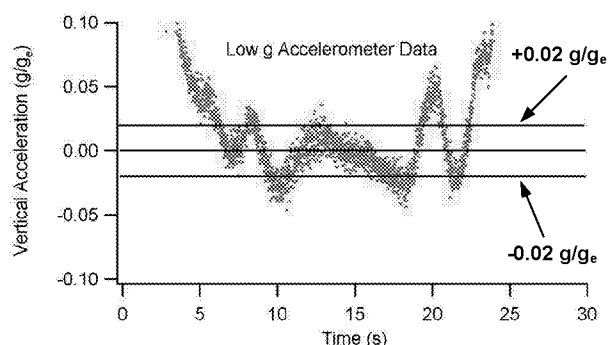


Figure 4
Typical acceleration environment aboard reduced gravity aircraft along the vertical axis of the aircraft

The acceleration environment was measured during the test using a 3-axis accelerometer system. While 'zero-gravity' is the goal, small amplitude, high frequency accelerations are routinely observed, with larger amplitude, low frequency accelerations observed at times. Figure 4 shows an acceleration plot typical of those observed throughout the test series. The horizontal lines indicate acceleration levels of 0.02, 0.0, and -0.02 g/g_e , respectively. Parabolas where the acceleration level was between $\pm 0.02 \text{ g/g}_e$ for the duration of the time between solder application and solidification were judged to be acceptable.

Visual Inspection

A visual inspection on the solder joints from the first two flight weeks yielded the results shown in Table 1. The inspection followed the standard set forth by NASA-STD-8739.3 (Ref. 4). Workmanship failures include excess or insufficient solder added to the joint, cold solder joint (insufficient heating which exhibits poor wetting), overheated solder joint, and poor or non-wetting joints. Void failures describe solder joints that have visually apparent holes or evidence of subsurface voids.

Cause of failure	Normal Gravity	Reduced Gravity
Workmanship	4.7%	10.7 %
Voids	3.1%	10.0 %

Table 1: Visual Inspection – Failure rates in normal and reduced gravity samples

Geometry

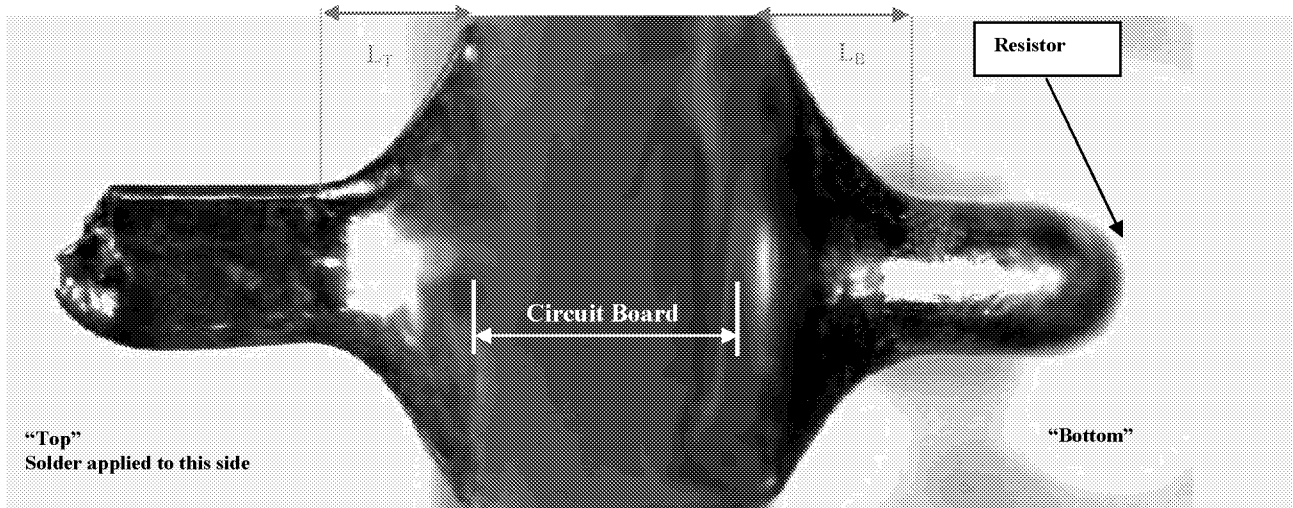


Figure 5
Front illuminated photograph of a solder joint used for leg length measurements

Each sample was photographed and the leg length of the “top” and “bottom” of the solder joint was measured as shown in Figure 5. The ratio of the leg lengths (top to bottom) is shown in Table 2. This table shows that the acceleration environment affects fillet geometry. In reduced gravity, the upper and lower legs are about the same length. In normal gravity, the lower leg is longer than the upper leg (the 20% change in normal gravity leg length between Week 1 & Week 2 is attributed to the sample orientation change, previously discussed). It is possible that the 0-g solder joints may respond differently than 1-g solder joints to operating stresses. We are currently investigating the implications of this result.

Reduced gravity	Week 1	1.14 ± 0.057
	Week 2	1.08 ± 0.081
Normal gravity	Week 1	0.87 ± 0.071
	Week 2	0.70 ± 0.040

Table 2: Vertical Leg Length (L_T/L_B) ratios

During the STS-57 Shuttle experiment, the crewmember made the observation that the shape of the solder joint appeared more convex than was expected. Samples from the current experiment were examined (subjectively) for this characteristic by means of visual inspection of the sample cross-sections. The fillet geometry of samples

produced in reduced gravity tended to exhibit a more convex shape than those produced in normal gravity. However, this change in overall shape may be attributable (at least in part) to an increase in the mass of solder used in the reduced gravity tests. Measurements of the solder mass used indicate that test operators tended to add more solder in the reduced gravity tests than in the normal gravity tests (Table 3). This trend was evident in 4 of the 5 operators in this data subset. Overall, the mass of the reduced gravity samples was about 9% greater than those soldered in normal gravity. No explanation of this observation is offered at this time, but this factor, combined with the changes in leg length (previously described) are likely to account for the perceived change in the overall shape.

	Operator 1	Operator 2	Operator 3	Operator 4	Operator 5
Normal gravity: Avg. mass added	0.023 g	0.026 g	0.032 g	0.028 g	0.030 g
Reduced gravity: Avg. mass added	0.031 g	0.027 g	0.037 g	0.022 g	0.032 g

Table 3: Mass of solder used by each operator in normal and reduced gravity tests.

Porosity Measurements

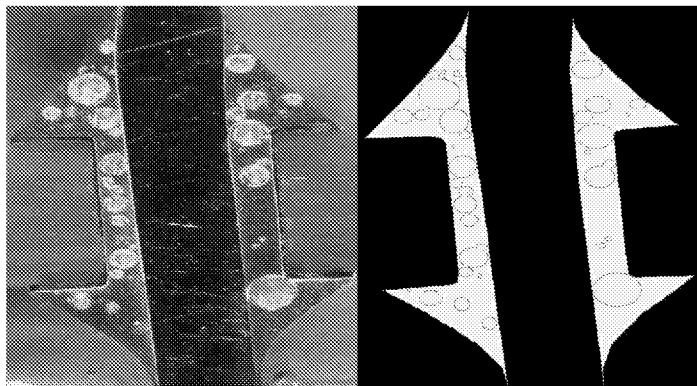


Figure 6

Image of joint, prepared for analysis. Pores are seen as circles in the joint.

Digitally enhanced image of joint, with yellow areas indicating pores & white areas indicating solid material.

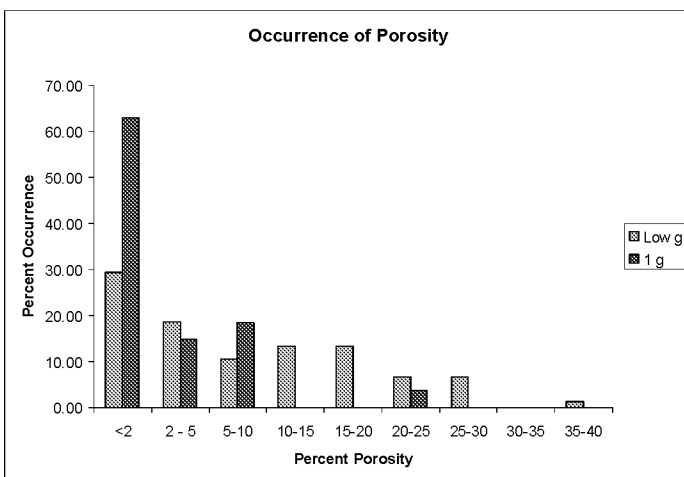


Figure 7

Rate of occurrence of porosity in normal and reduced gravity samples

Samples from the first two flight weeks were examined for internal porosity content by mounting the samples in 'metallographic' mounts and grinding them down to approximately the sample centerline. The percentage of porosity exposed by this was then measured by imaging the sample, designating (via computer program) what areas were 'void' (porous) areas, and dividing that area by the total area of the sample. This technique complies with ASTM Standard E1245-00 (Ref. 5), which addresses porosity measurements. This technique was carried out for both normal gravity and reduced gravity samples for the first two flight weeks. Figure 6 illustrates an example of a sample (after mounting and grinding) along with a digitized image showing the area measurement.

Results of this analysis are displayed in Figure 7, which is a bar chart showing the occurrence of porosity as a function of the percentage of porosity. The colored bars (blue for reduced gravity, red for normal gravity) indicate the rate of occurrence of samples with a given porosity content. For example, the set of bars on the far left of the plot indicate that about 63% of the normal gravity samples showed 2% or less porosity, while about 29% of reduced gravity samples displayed 2% or less porosity.

Overall, this plot indicates that about 96% of normal gravity samples show porosity rates of 10% or less, while only about 58% of the reduced gravity samples show 10% or less porosity. The hypothesized reason for this is that liquid flux vaporized and was trapped in the liquid solder (in the reduced gravity cases); without the presence of gravity to drive these gas bubbles out, they solidified into the pores seen in these measurements.

Thermocouple Data & Cooling Times

Thermocouple junctions spot-welded or soldered to the joint provided temperature traces for a subset of both the normal and reduced gravity tests. Figure 8 shows representative temperature data for both cases.

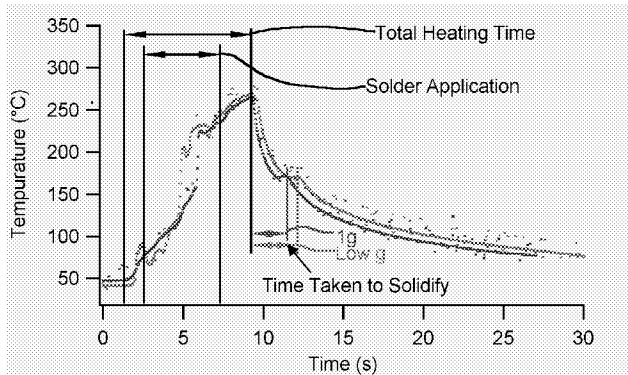


Figure 8
Representative temperature measurements of the soldering process

Events such as solder application and solidification time were determined through examination of the video data, and temporally correlated to the thermocouple data. The cooling time (for solidification) determined from this data was compared to the video data by looking for evidence of phase change. The temperature data correlated well with the visual data, allowing the image data to give cooling times for all tests (including samples without thermocouples). This data is compiled in Table 4, along with the average mass of the samples.

	Normal gravity	Reduced gravity
Average Sample Mass	0.0261 g	0.0285 g
Average Solidification Time	2.79 sec	2.96 sec

Table 4: Average sample mass and solidification times for normal and reduced gravity samples

This shows that, although the solidification time was about 7% greater in the reduced gravity samples (compared to the microgravity samples), this is accounted for by the increased mass of the reduced gravity samples, with the slightly larger samples having a greater thermal inertia.

DISCUSSION AND CONCLUSIONS

The effect of reduced gravity on the soldering process was examined in a plated through-hole configuration aboard a reduced gravity aircraft. In the absence of gravitational forces, geometric changes (as measured by the ratio of the ‘leg’ lengths of the joint on the top and bottom of the board) were observed; in reduced gravity, the joint ‘leg’ on the top surface (where solder was applied) was longer than that on the bottom side, whereas in normal gravity, the bottom side had greater leg lengths.

Samples soldered in reduced gravity were (subjectively) observed to be more convex than those produced in normal gravity. However, measurement of the mass of solder applied revealed that on average, about 9% more solder was applied during reduced gravity tests. This additional mass, combined with the measured changes in leg length of the joint, may account for the slightly more convex shape of the reduced gravity samples. The increased mass is also likely to account for the slight increase in solidification times (as measured by thermocouples and video analysis) for the reduced gravity samples.

Significantly more visual defects and internal porosity were also observed in the reduced gravity samples. A reasonable explanation for this could be that flux is trapped in the liquid solder, and after vaporization, the bubbles are unable to migrate to the surface due to the lack of buoyant forces. These trapped bubbles are then preserved as porous voids in the joint after solidification.

Due to this observed increase in porosity in reduced gravity samples, efforts were made to mitigate the porosity through a procedural change. Instead of using a flux-cored solder (as is currently manifested on ISS), solid-cored solder (along with liquid flux) was used. Liquid flux was applied first, and (after application of the soldering iron) allowed to vaporize before application of the solid solder. If the hypothesis that entrapped flux is responsible for the increased porosity is correct, this approach may help mitigate the problem. Data from this flight week is currently under analysis, and will be presented in a future paper. The possibility of an on-orbit ISS experiment is also being examined, to validate the recommendations for porosity abatement that will come from the current efforts.

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